



# 2003 AFCEE Technology Transfer Workshop

San Antonio, Texas

*Promoting Readiness through Environmental Stewardship*

## Anaerobic Bioremediation of Chlorinated Solvent Source Areas – What Can Be Achieved?

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**Solutions-IES**  
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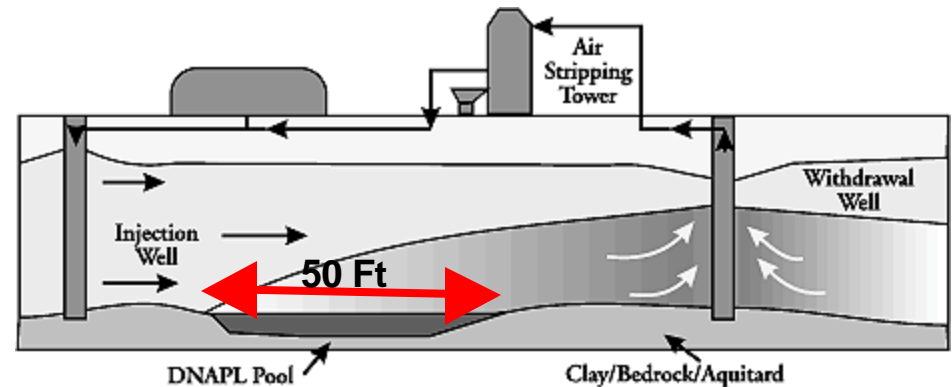


**Air Force Real Property Agency**



# ***Problems with Pump & Treat***

- Pump and treat systems can remove significant amounts of dissolved contaminants
- High O&M costs
- NAPL removal is limited by dissolution kinetics
  - Chlorinated solvents have moderate to low solubility
  - Slow mass transfer rates



Source: Dick Jackson



# ***DNAPL Dissolution - No Biodegradation***

## ■ **NAPL Dissolution Rate**

$$dC/dt = K_m A (C_s - C)$$

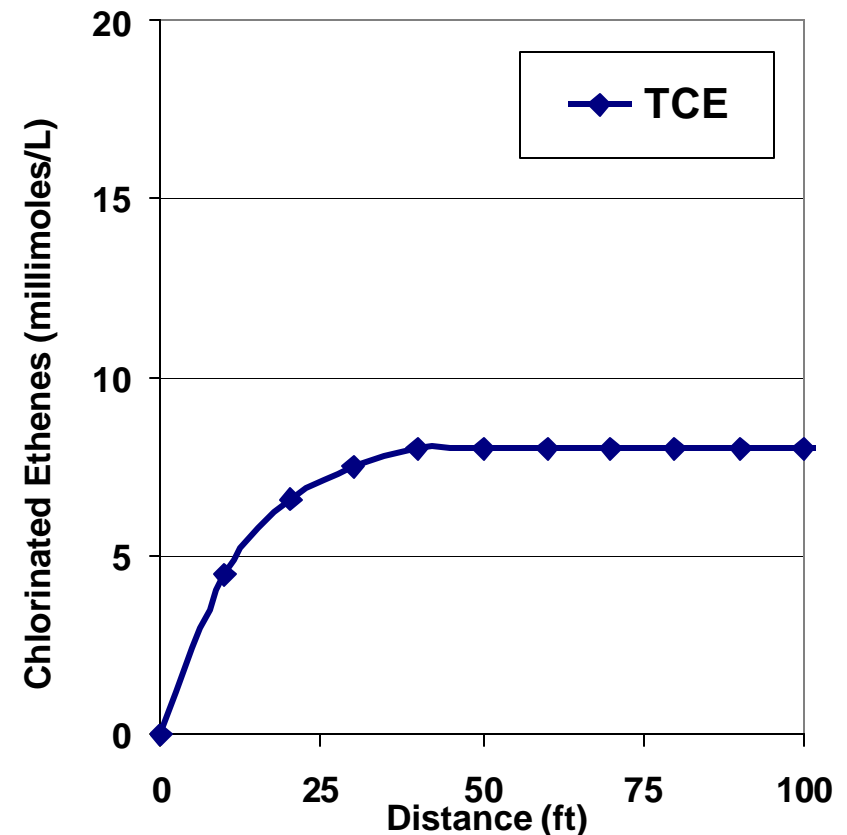
**C** = dissolved conc.

**T** = time

**K<sub>m</sub>** = mass transfer rate

**A** = NAPL-water  
contact area

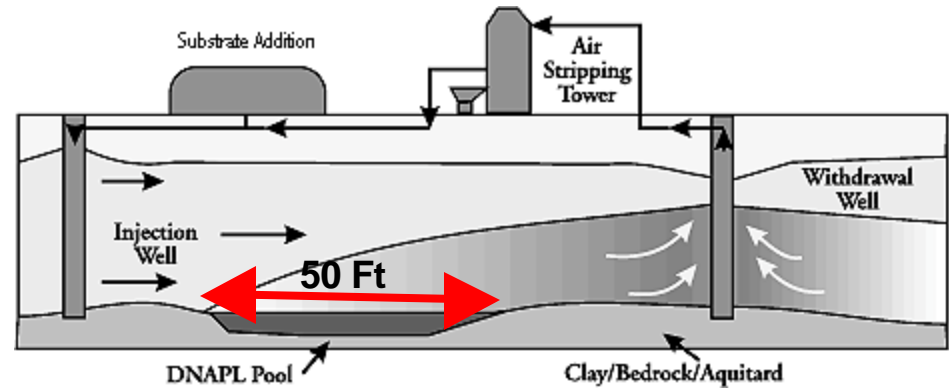
**C<sub>s</sub>** = NAPL solubility





# ***Enhanced Anaerobic Bioremediation***

- **Same basic system as pump & treat**
  - Inject water containing biodegradable substrate
  - Flush past contaminant
  - Recover and circulate
- **High O&M**
  - Substrate addition
  - Monitoring and process control
  - Biofouling of wells, infiltration basins and piping
- **Benefit – increased dissolution**





# DNAPL Dissolution with Biodegradation

## ■ Anaerobic Biodegradation

NAPL ? TCE

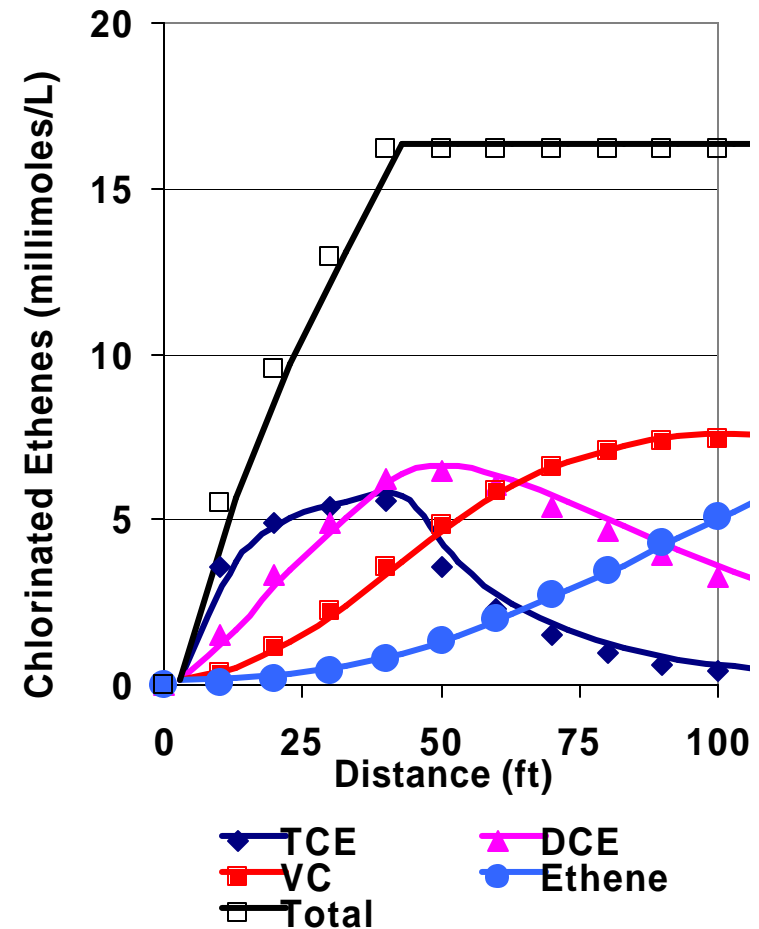
TCE ? DCE ? VC? Ethene

$$\frac{dTCE}{dt} = -K_{TCE}TCE$$

$$\frac{dDCE}{dt} = +K_{TCE}TCE - K_{DCE}DCE$$

$$\frac{dVC}{dt} = +K_{DCE}DCE - K_{VC}VC$$

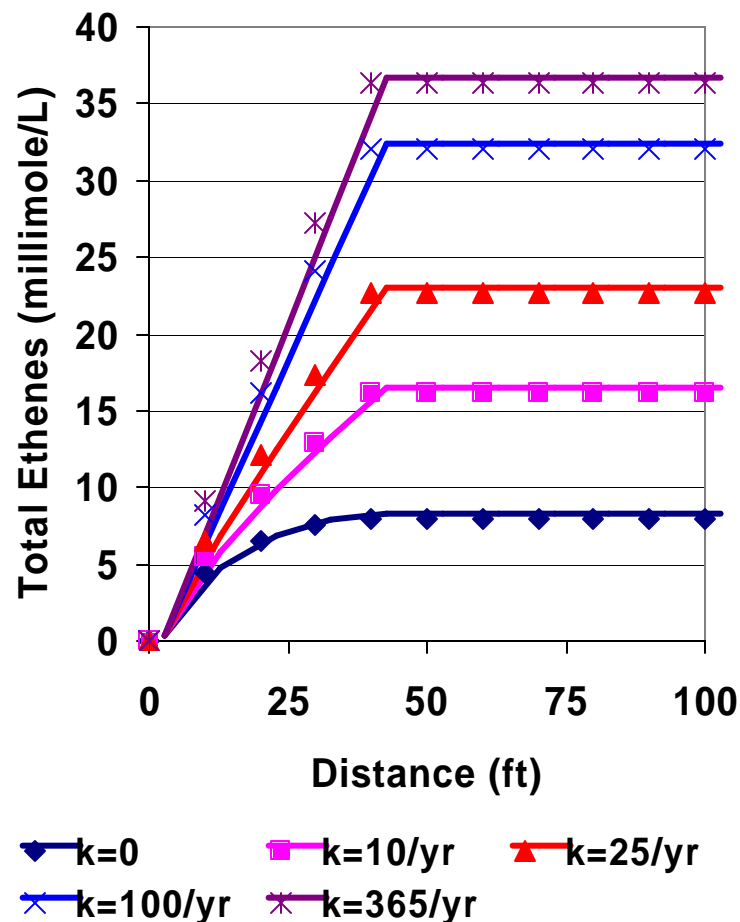
$$\frac{dETHENE}{dt} = +K_{VC}VC$$





# *How Bioremediation is Supposed to Work*

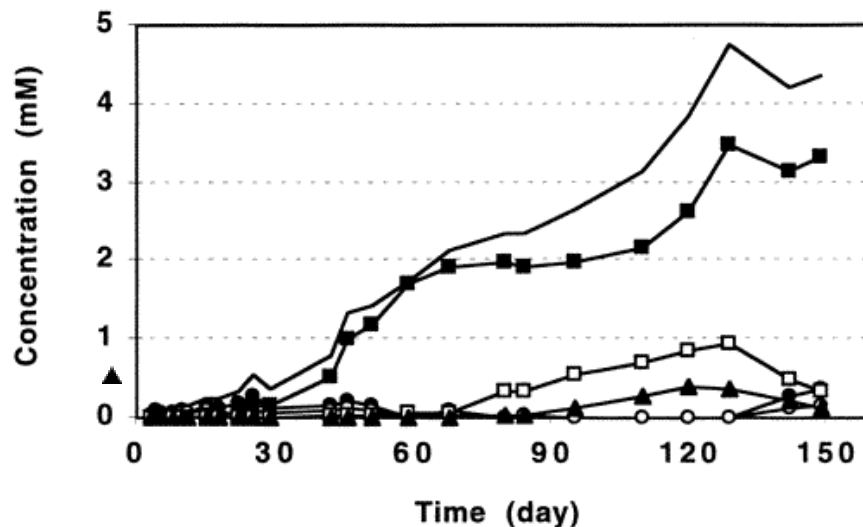
- Higher Biodegradation rates reduce aqueous TCE concentration
- Lower dissolved TCE conc. increases dissolution rate causing more rapid TCE removal





# Laboratory Results

- Yang and McCarty (2000)
  - Column containing residual PCE
  - PCE Solubility = 150 mg/L  
■ = 0.9 mM
  - Columns fed pentanol
  - Large production of c-DCE
  - Total ethenes = 4 – 5 mM
- Biodegradation increased PCE dissolution by 500%



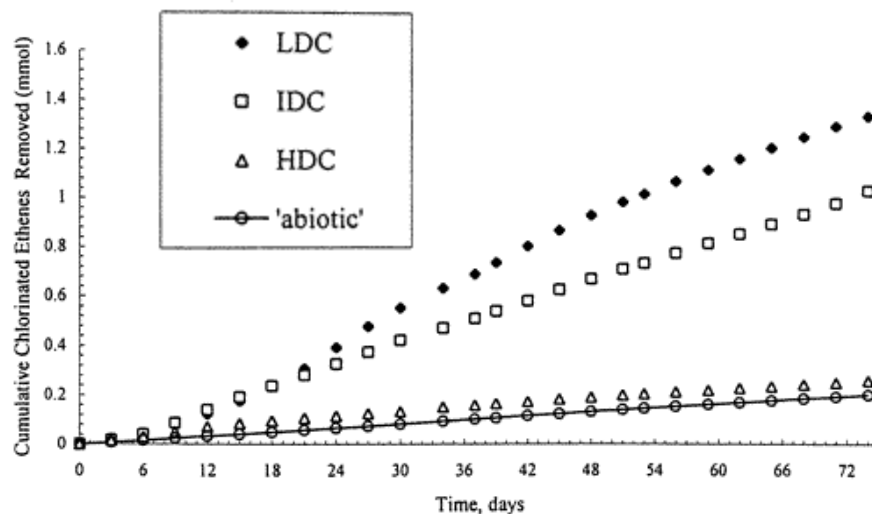
● PCE                      ? TCE  
■ cDCE                    □ VC  
? ethene                  -- total



# Laboratory Results

## ■ Cope and Hughes (2001)

- Columns containing PCE / tridecane
- High substrate column - no dechlorination
- Moderate substrate column
  - 16 times increase in PCE removal
  - 6.5 times increase in total ethene removal
- Low substrate column
  - 5.0 times increase in total ethene removal

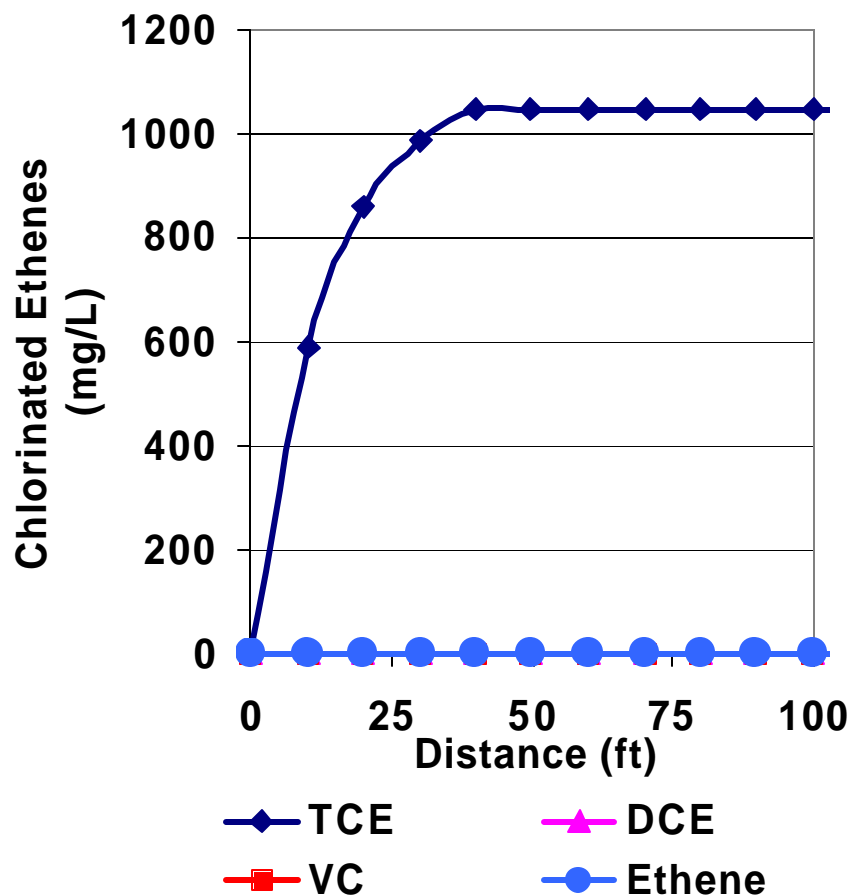




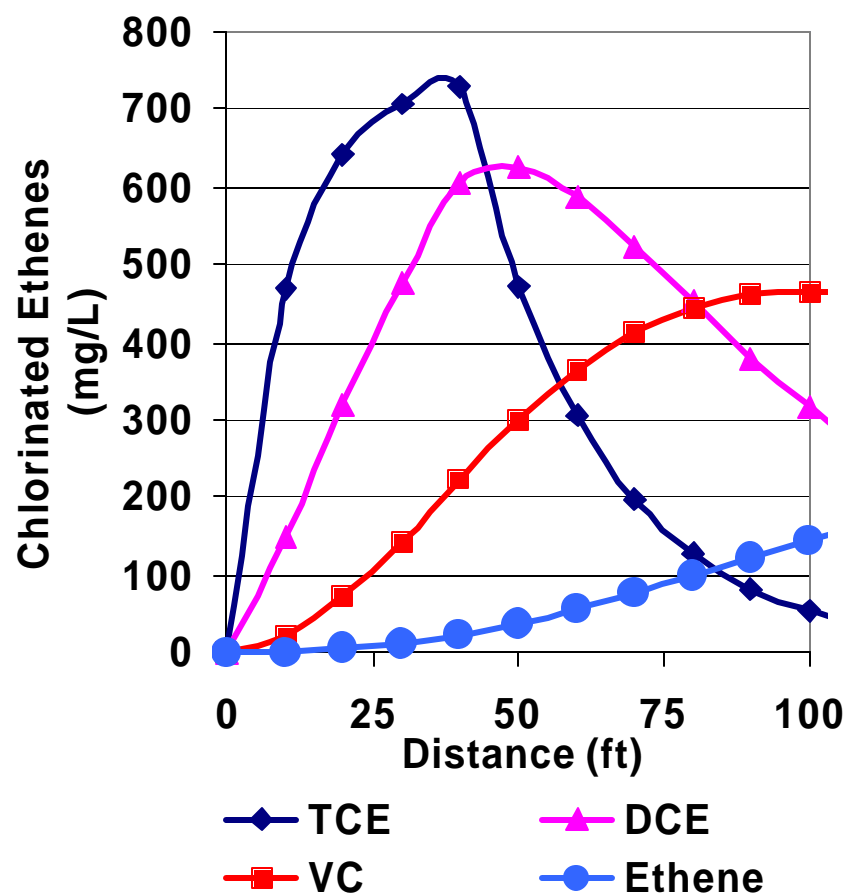


# NAPL Dissolution – High Mass Transfer Rates

## No Biodegradation



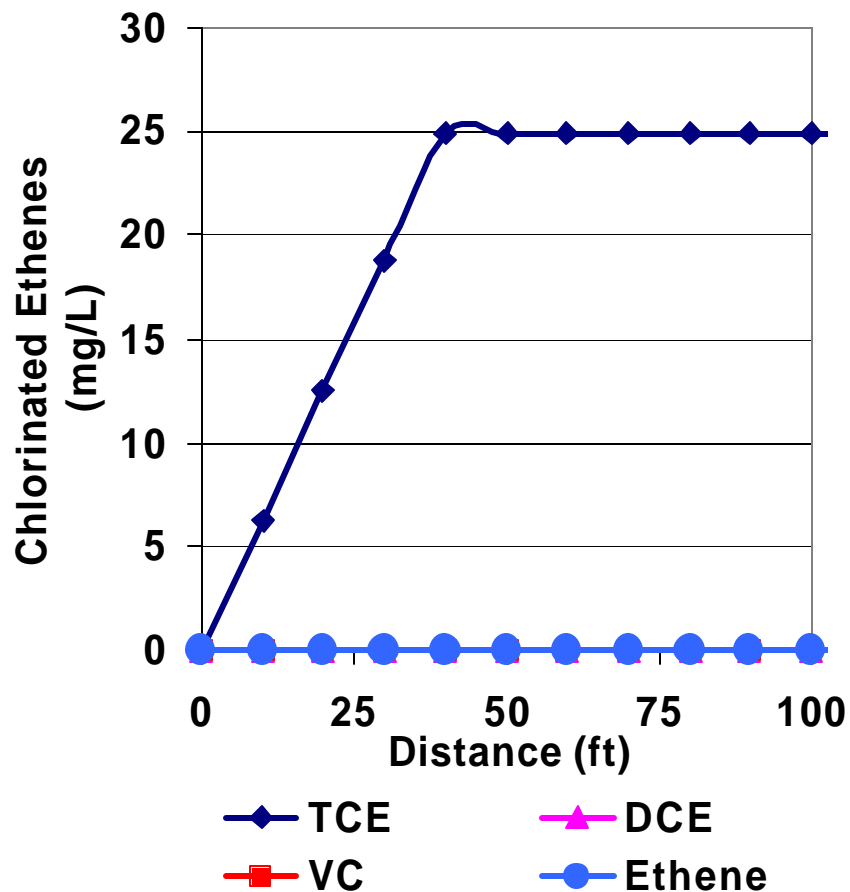
## Enhanced Biodegradation



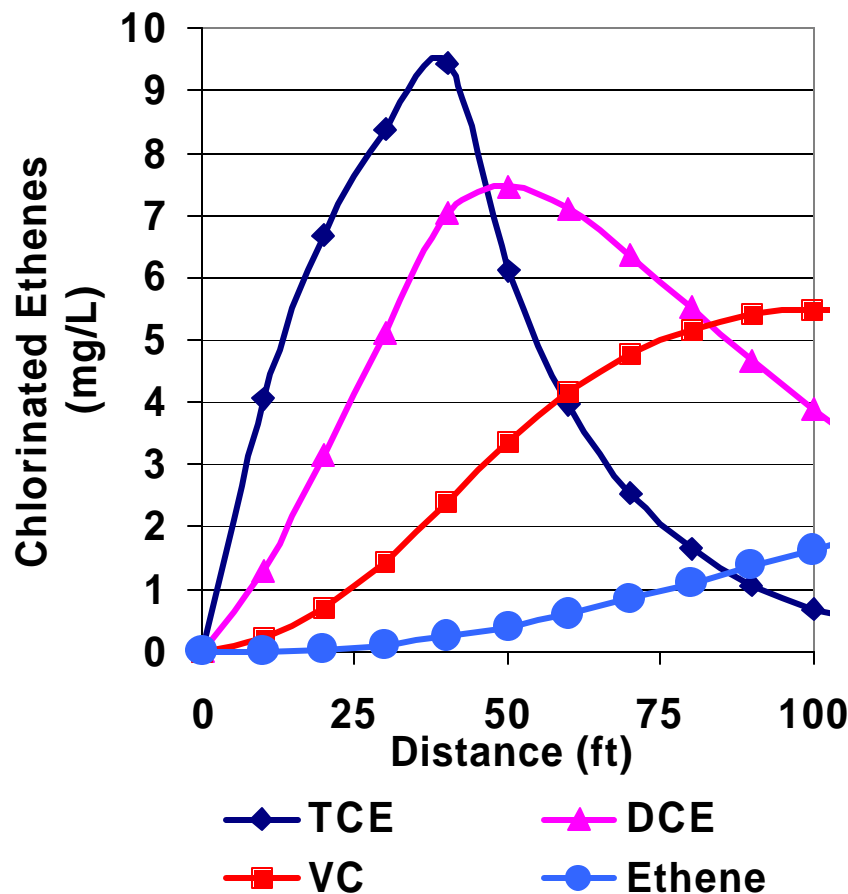


# NAPL Dissolution – Low Mass Transfer Rates

## No Biodegradation



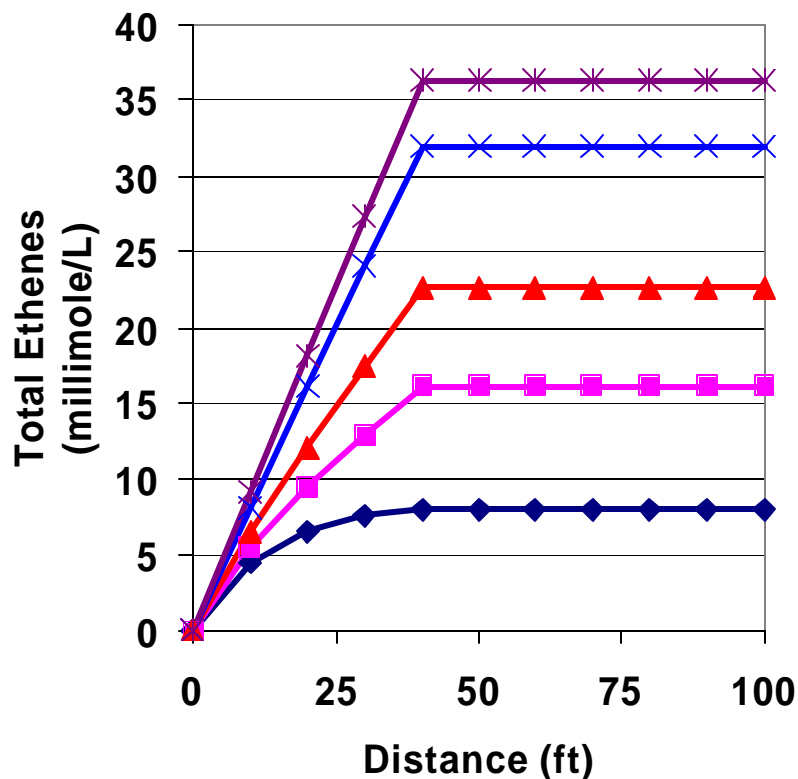
## Enhanced Biodegradation





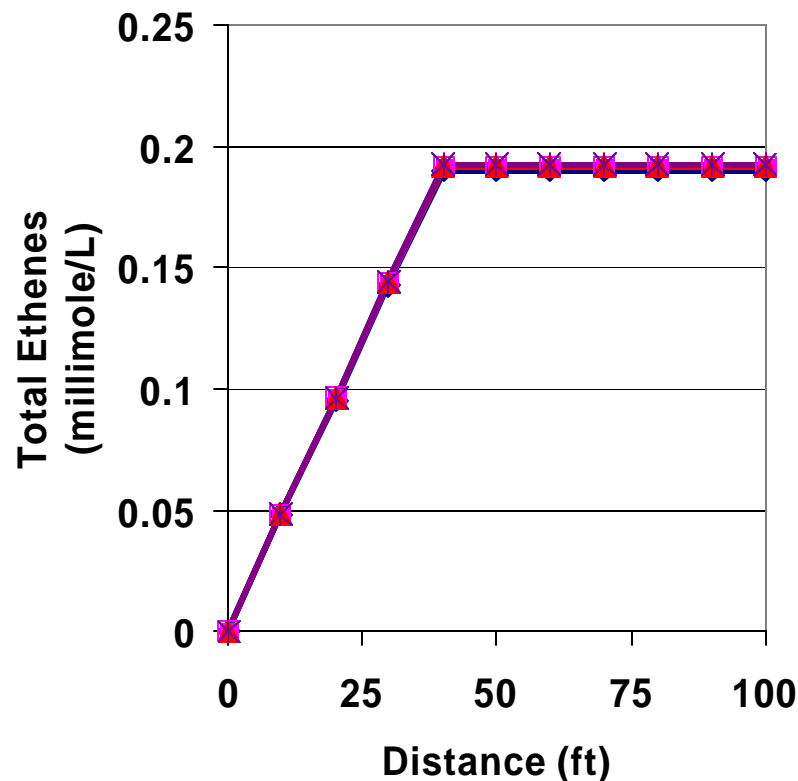
# Impact of Mass Transfer on NAPL Removal

## High Mass Transfer Rate



◆ k=0    ■ k=10/yr    ▲ k=25/yr  
✕ k=100/yr    \* k=365/yr

## Low Mass Transfer Rate



◆ k=0    ■ k=10/yr    ▲ k=25/yr  
✕ k=100/yr    \* k=365/yr



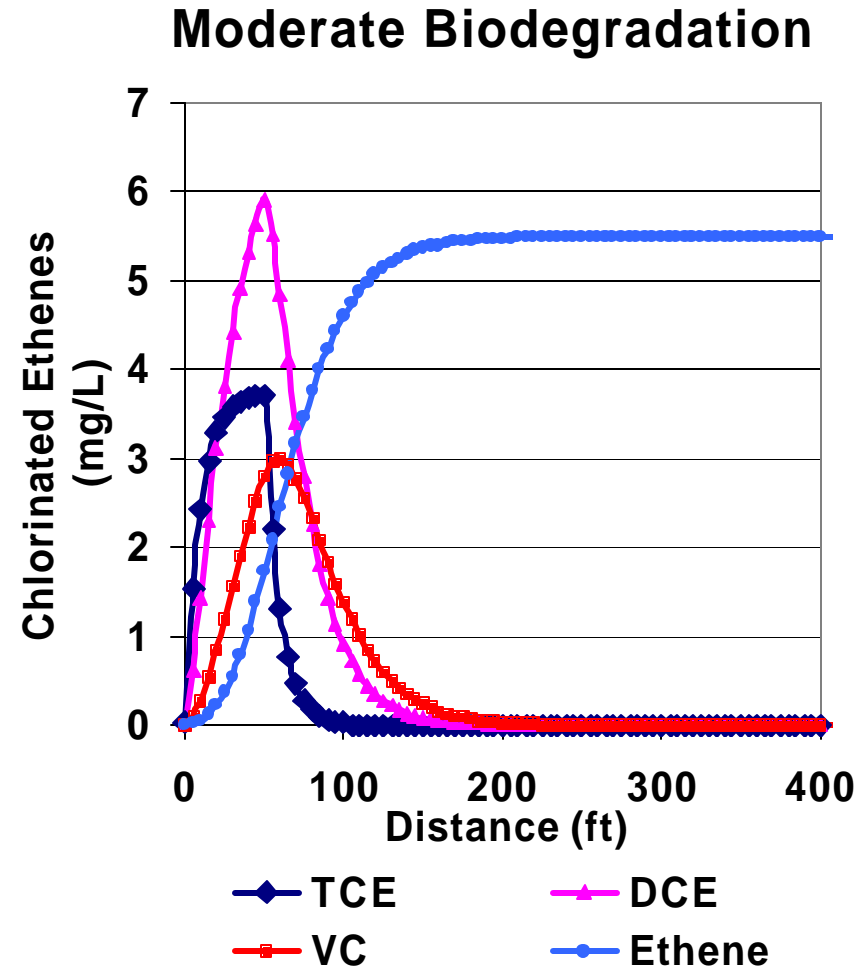
# ***What can Bio-dissolution Achieve?***

	High Mass Transfer Rate	Low Mass Transfer Rate
Average NAPL Saturation	0.1	0.005
NAPL Mass (Kg)	5,000	250
No Biodegradation		
Max. TCE Concentration (mg/L)	730	25
Dissolution Rate (g/d)	250	8.7
Source Half-life (years)	27	39
Rapid Biodegradation ( $k=1/d$ )		
Dissolution Rate (g/d)	430	8.9
Source Half-life (years)	16	39



# ***Bioremediation for Source Containment***

- **Enhanced biodegradation can control down gradient migration of dissolved solvents**





# ***INEEL Results***

- **Liquid wastes injected into fractured basalt aquifer (1950's – 1970's)**
  - **Sewage**
  - **Cooking wastes (oil and grease)**
  - **Chlorinated solvents (DNAPLs?)**
  - **Petroleum**
  - **Radionuclides**
- **Monitoring data showed evidence of reductive dechlorination**
- **Remediation approach – pulsed addition of soluble substrate (organic acids) to original injection well**

# Site Plan

## Injection System



TCE  
Isopleths

## Air Stripper

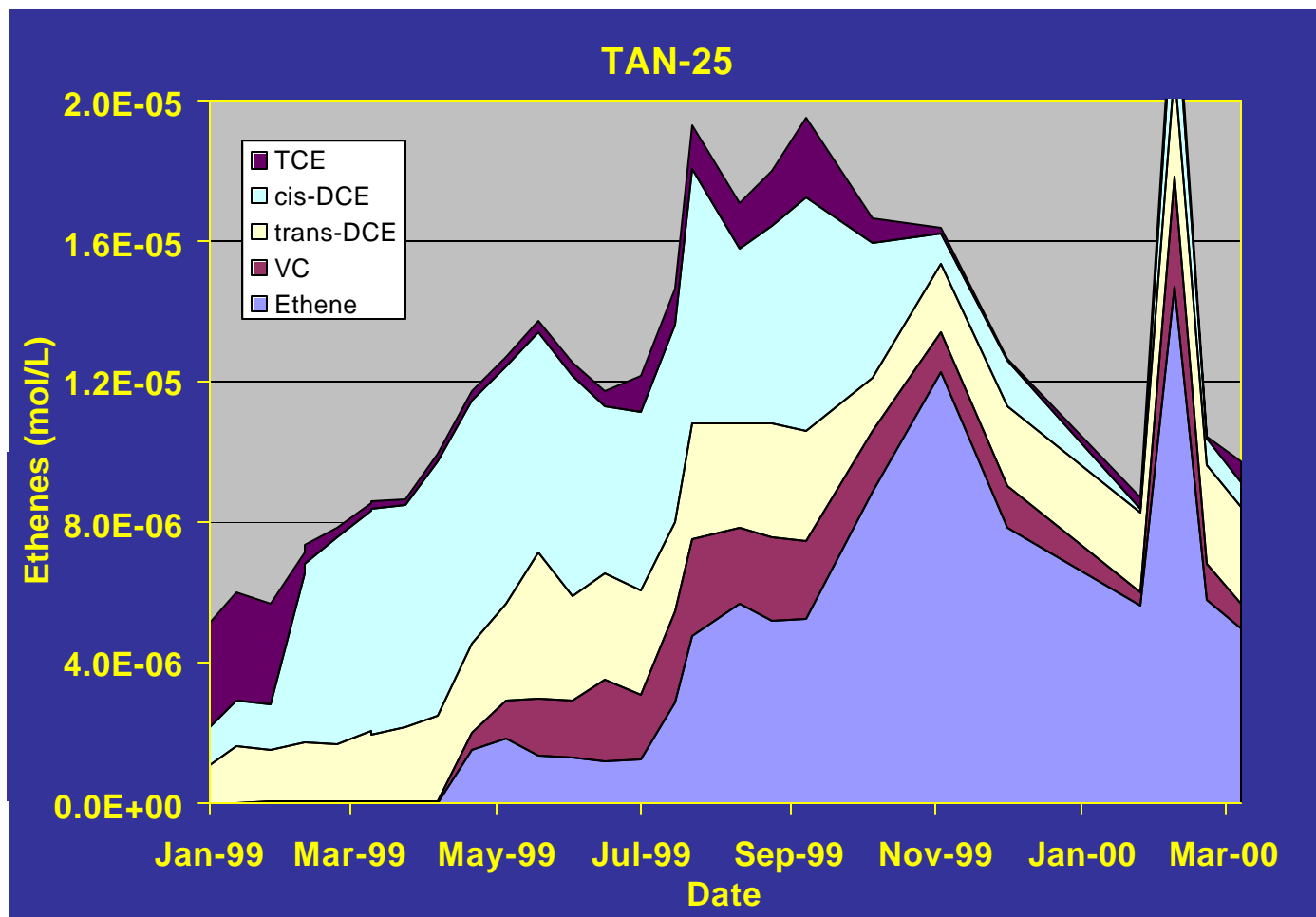


- Air Stripper Wells
- Monitoring Wells
- Injection Well

0 100 200 300  
Feet



# INEEL Results

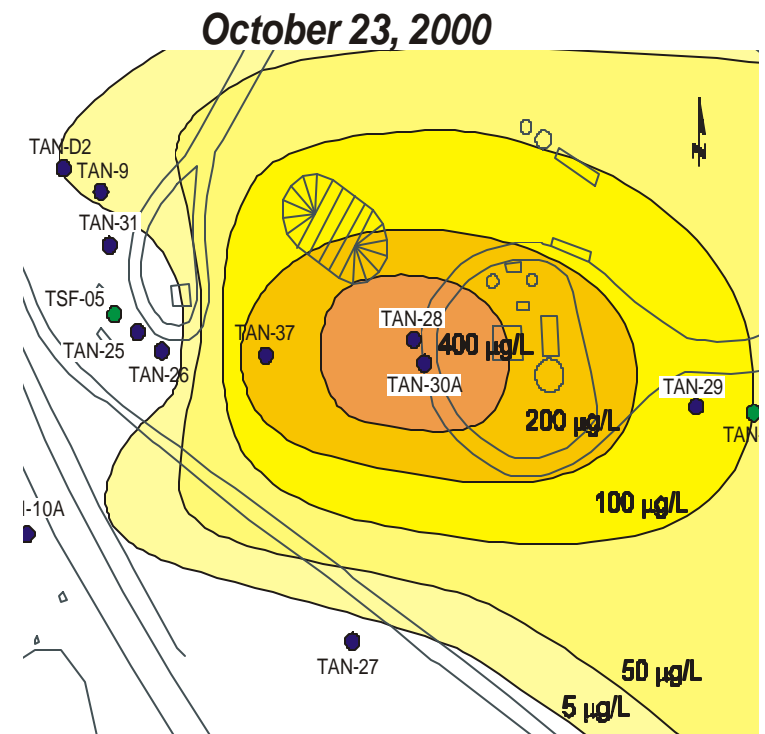
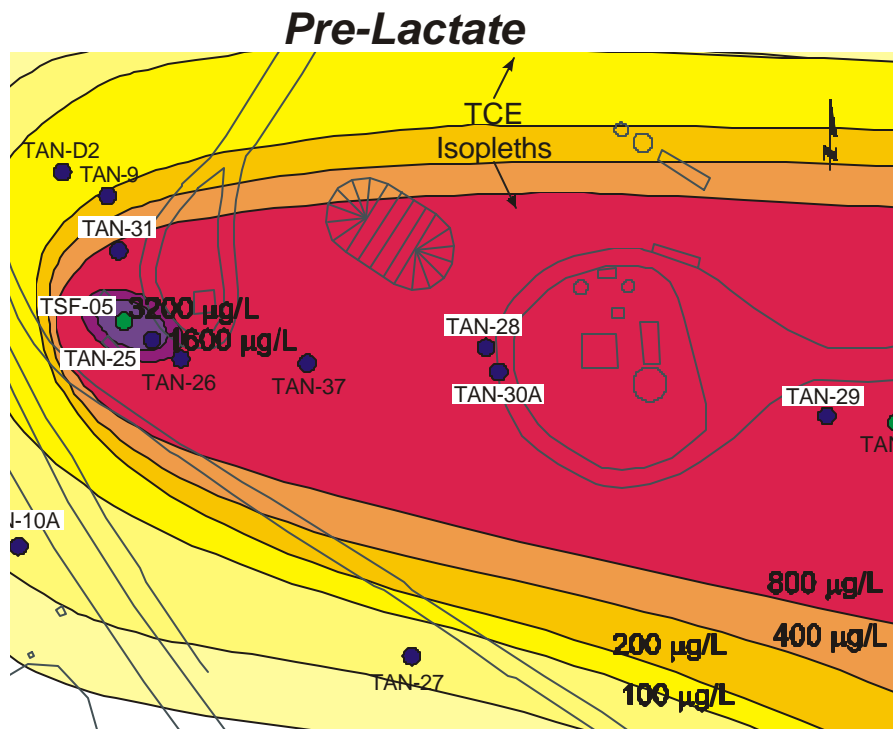






# INEEL Results

- Lactate addition has resulted in major reduction of TCE plume





# ***Conclusions***

- **Highly contaminated source areas**
  - **Pump and treat will take a very long time to cleanup source**
  - **Enhanced bioremediation can increase amount of NAPL dissolved**
  - **Biologically enhanced pump and treat will still take a very long time to cleanup source**
  - **O&M costs are higher than for conventional P&T**



# ***Conclusions***

- **Lightly contaminated source areas**
  - **Aqueous phase concentrations are moderate to low**
  - **Pump and treat will take a very long time to cleanup source**
  - **If contaminant removal by pump and treat is mass transfer limited, enhanced bioremediation will have very little impact on NAPL removal rate**



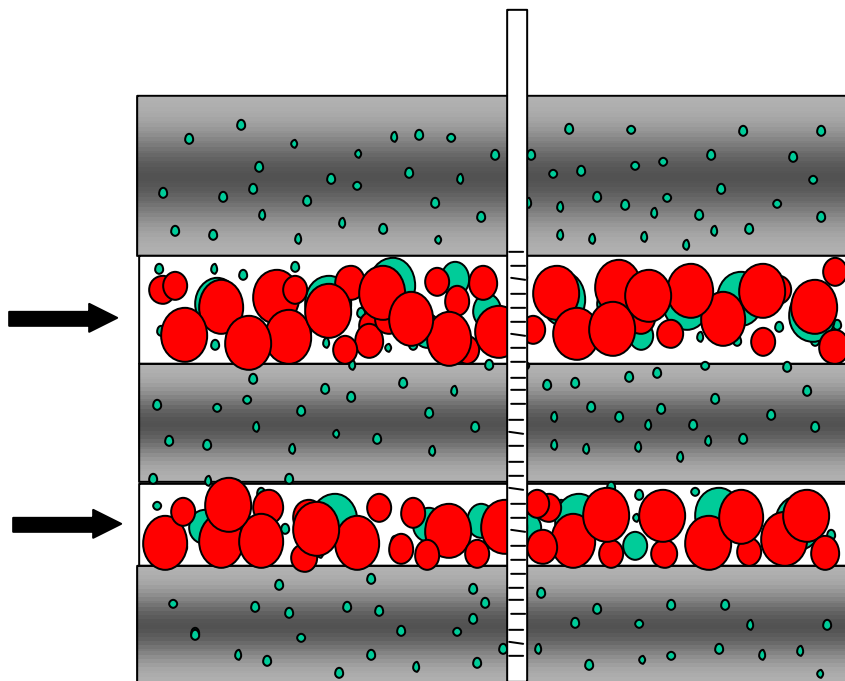
# ***Conclusions***

- **Biologically Enhanced Source Containment**
  - **Anaerobic biodegradation can prevent downgradient migration of dissolved solvents**
  - **Requires regular operation and maintenance**
    - **Substrate addition**
    - **Process monitoring**
    - **Biofouling issues**



# ***Containment using Edible Oils***

- **NAPLs preferentially enter high K layers**
- **Groundwater flow through these high K zones enhances contaminant mass flux**
- **Solution -- Inject food-grade edible oils in source area to reduce dissolved mass flux**





# ***Benefits of Edible Oil Injection***

- **Short-term**
  - **Reduce permeability**
  - **Reduce effective solubility of contaminants**  
$$C_{\text{effective}} = \text{Solubility} * \text{Mole Fraction}$$
  - **Enhance biodegradation of contaminants that are release**
  - **Net result ? lower contaminant mass flux, lower risk to downgradient receptors**
- **Long-term**
  - **Enhanced biodegradation of contaminants**